NASA ADVANCED CONTROL TECHNOLOGY: AN OVERVIEW

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ABSTRACT

NASA's current and projected advanced control technology programs for future transport aircraft include the design and verification of full-flight envelope autopilots, the development and flight test of all-digital fly-by-wire systems, the evolution of low-cost innovative avionics concepts such as split surface stability augmentation systems, the evaluation of integrated propulsion control and cooperative autopilot/propulsion control systems, the application of active control systems to short-haul and long-haul transports, and the demonstration of reconfigured active-control aircraft. Key technical features and anticipated contributions of these technologies are outlined.

INTRODUCTION

With the advent of digital microelectronics, practical design of a new class of transport aircraft with significant performance gains and weight savings through active controls has become feasible. NASA is conducting several research and development programs specifically aimed at generation of the critical technology for such

advanced control aircraft and for the associated digital flight control systems. This paper provides an overview of these programs.

Other ongoing NASA efforts, such as the development of highly-reliable, easily-maintainable computer systems or automatic landing systems - essential but not unique to active controls - are not treated here. NASA-sponsored aircraft design studies concerned primarily with the definition of advanced control technology requirements and benefits for future transports - but not including control research and development efforts - are also omitted.

TECHNOLOGY OVERVIEW

NASA advanced control programs can be naturally broken into the development of improved control systems and into the application of the resultant control concepts for the design of more efficient transport aircraft. Figure 1 introduces the related activities. Work on advanced control systems is addressed by programs on full flight envelope autopilots (FFEAP), digital fly-by-wire systems, innovative avionics systems, and propulsion control systems. The extension of these control capabilities to the definition and validation of advanced aircraft designs will be addressed by the active control aircraft and the proposed active-control-configured transport programs.

Major design and flight test milestones, indicated on the figure, for the NASA programs, will be outlined in the specific summary of each program. Completion of these design and verification tasks by the early 1980's is planned to permit the incorporation of advanced control concepts in the next generation of transport aircraft - currently projected to enter service in the mid to late 1980's.

Full-Flight-Envelope Autopilots

Under the first program on improved controls, the Ames Research Center is investigating the application of optimal control theory to the design of full flight envelope autopilots (reference 1). The associated design approach is illustrated in figure 2. The aircraft is calibrated over the entire flight regime by trim maps which tabulate lift, drag, and moment coefficients versus critical aircraft variables such as angle of attack and flap angle. The control deflections required to obtain a commanded acceleration can then be calculated from these trim maps, with feedback used to compensate for mismatch between the trim maps and the actual aircraft characteristics. The result is a linear acceleration command system, and linear optimization theory can be applied to define desirable overall trajectory and attitude control algorithms.

Detailed design of this full-flight-envelope autopilot (FFEAP) is presently underway and is expected to be completed in mid 1975. Following FFEAP validation during six-degree-of-freedom simulations in 1976, the first implementation of the FFEAP is planned as an experiment, the FFEAP algorithms will be programmed on the onboard STOLAND system, and evaluated during representative flight operations. If proven successful, follow-on flight tests of the FFEAP system will be conducted on short-haul powered-lift aircraft, such as a tilt-rotor configuration, in late 1978.

Preliminary FFEAP results indicate that the optimized controller mechanization could significantly increase transport aircraft performance over the entire flight envelope, and could minimize delays and fuel consumption during terminal area operations.

Digital Fly-By-Wire Systems

A companion NASA control system program, conducted jointly by the Flight Research Center and the Langley Research Center, involves the development and flight verification of digital fly-by-wire (DFBW) systems. The basic phases of this program are represented in figure 3. Phase I (references 2-4) has demonstrated the feasibility and performance of DFBW control using

Apollo hardware in a single-channel primary system with a triplex analog backup system (reference 5) installed in an F-8 aircraft. Direct, stability augmentation, and command augmentation system modes were successfully evaluated during approximately 18 months of flight testing. For Phase II, the Phase I fly-by-wire systems will be replaced by a triplex all DFBW system using aircraft-compatible computers and sensors. The all-DFBW system will then serve as a test bed for early verification of critical Space Shuttle software concepts and for flight implementation of several advanced control law concepts. The first of these, summarized in figure 4, will investigate performance improvements obtainable through synthesis of selected control configured vehicle (CCV) concepts. Specific CCV systems considered include static stability augmentation, maneuver and gust load control, and envelope limiting. The associated control algorithms were designed through an iterative quadratic optimization process (reference 6), and are being validated during laboratory simulations at the Langley Research Center. After software coding and iron-bird checkout of the CCV algorithms, first flight tests of the CCV system are scheduled for mid 1976.

The second advanced control study, illustrated in figure 5, addresses the mechanization of an adaptive control system compatible with potential transport

applications. Candidate concepts under investigation are an implicit identification scheme (reference 7) involving multiple-model hypothesis testing; and two explicit identification schemes based on different techniques for parameter identification and control optimization. The first uses a recursive, weighted-least-squares identifier, and an algebraic equation to determine the control changes from the previous commands (reference 8). The second uses a modified Newton-Raphson technique for identification. Other potential advanced control approaches being considered for flight test include self-organizing systems (references 9-10), which can automatically restructure themselves to accommodate sensor and actuator failures with considerable attendant reliability increases; and learning control systems with the capability to evolve improved aircraft modeling and estimation techniques during flight. The most promising of these control concepts will be selected for flight implementation in 1976. In-flight tests on the F-8 will then be conducted in 1977, following mechanization and ground verification of the resultant flight control systems.

Current Flight Research Center plans for the total redundant DFBW systems tests call for a 30 month flight test program beginning in 1976. Approximately six months will be devoted to validation of the basic system.

configuration and to inflight verification of Space Shuttle software designs. The remainder of the program will be available for the advanced control law tests.

Innovative Avionics Systems

Besides these efforts on the exploitation of digital control, work at the Flight and Ames Research Center is concerned with the design and mechanization of innovative avionics systems which could reduce avionics cost through simplification and modularization. While the primary users of such concepts will be general aviation aircraft, many of the associated design philosophies may be applicable to transports as well.

One of these concepts, depicted in figure 6, involves the development and flight demonstration of a separate surface stability augmentation system (SSSAS) on a Beech 99 commuter airlines under a contract managed by the Flight Research Center. With this approach (reference 11), the aircraft control surfaces are split into primary and secondary segments, and the separate secondary surfaces are incorporated in a limited-authority ride smoothing and gust alleviation system. Since the primary control system can overide the secondary system in case of a hard-over failure, the SSSAS may be mechanized with single-string, low-cost components with considerable associated system cost

savings. Major improvements in ride quality are expected through this approach, which will be validated during extensive flight tests in 1975.

Another low-cost avionics program, conducted by the Ames Research Center, focuses on the design of integrated avionics systems which take maximum advantage of recent advances in microelectronics and digital circuit technology. The design philosophy for this system, illustrated in figure 7, will be initiated with subsystem concept studies and 1980 technology and air traffic projections. The resultant specifications and requirements will be used to define candidate modular avionics systems. The most cost-effective of these systems will be carried through subsystem development and final design by 1979; and will be evaluated through piloted flight simulations in 1980.

Propulsion Control Systems

The application of advanced control techniques to the optimization of aircraft propulsion systems performance can also result in large improvement in engine thrust and fuel economy. Two related NASA programs, conducted jointly by the Flight and Lewis Research Centers, are concerned with the development of integrated propulsion control systems (IPCS) and with cooperative aircraft and propulsion control.

For the first of these efforts, the Air Force and NASA have undertaken a joint program (reference 12) to demonstrate inflight the benefits obtainable from an integrated propulsion control system in an F-111 aircraft. The associated design philosophy, indicated in figure 8, utilizes a high-response control system which rapidly senses changes in flow conditions and uses a digital controller to command engine inlet geometry configurations needed for optimal propulsion performance. Such an IPCS can minimize stall margin throughout the flight environment, and could permit significant reduction in current engine safety margins, with attendant increases in range projected as large as 10 percent. The F-111 IPCS is slated for flight tests in 1975.

A second NASA effort on propulsion control involves the integration of the propulsion and aircraft control systems (reference 13) for the YF-12 research vehicle. The analysis of supersonic flight tests on the XB-70 and YF-12 indicate that airframe/propulsion system interactions are the primary cause of altitude fluctuations in supersonic cruise, of poor lateral-directional characteristics, and of severe transients during inlet unstarts. It is clear from these flight results that the propulsion system cannot be treated independently from the aircraft control system. A proposed integrated

airframe/propulsion control system, shown in figure 9, thus incorporates a digital control system which combines the inlet, engine and airplane flight controls. The longitudinal phase of this cooperative control system will be flight tested on a YF-12 in 1975, followed by YF-12 flight tests of the lateral directional phase in 1976. Design specifications for a total cooperative control system, based on these interim test results, are expected to be available by late 1977.

The most significant payoff of the advanced control approaches discussed so far requires consideration of their capabilities in the selection of the initial aircraft configuration through a new aircraft design approach which permits full tradeoffs between aerodynamics, structures, and control for the designated mission requirements. With this active control design approach, reductions in the aircraft natural aerodynamic stability and structural loads could be obtained through reliance on the damping and load control capabilities of a flight-critical automatic control system. These reductions in turn can permit large savings in aircraft gross weight and fuel. NASA is conducting two programs to provide and verify the critical technology required for early application of such active control designs in future civil transports.

Active Control Aircraft

The Active Control Aircraft (ACA) program, carried out by the Langley, Flight and Ames Research Centers, concentrates on development of the integrated active control system and aircraft design technology to meet the needs of new short-haul and long-haul transport designs in the early 1980's. Initial work will focus on the formulation of an adequate modeling and analysis base for ACA design. Specific associated tasks include the generation and validation of transonic aerodynamic pressure distributions for deflected and oscillating control surfaces, of aeroelastic design programs for flutter suppression, of prediction techniques for aircraft structural dynamics and static deformations, and of insensitive control techniques which allow for uncertainties in the aircraft aerodynamic and structural parameters. An integrated conceptual design program incorporating these modeling and analytical procedures for ACA will be derived to permit incorporation of all the active control functions into a workable system, and selection of the most cost-effective aircraft configuration for a given mission. One of the approaches under consideration for the conceptual design process is outlined in figure 10. After specification of general configuration guidelines and mission requirements, this

computer-aided design program defines the initial aircraft geometry and uses a quadratic optimization procedure to converge on suitable final configurations. An economic assessment subroutine is then employed to determine the best of these alternate configurations, and to select the final active control aircraft and system designs. To provide the necessary system and aircraft inputs for this approach, wind tunnel tests and validation flights, using DHC-6 and subsonic transport "test beds", are planned in 1976 and 1977.

The next phase of the program involves the extension of this initial work into specific short-haul and long-haul transport applications. For the short-haul application, depicted in figure 11, a ride quality and precise trajectory tracking system will be designed and installed on a DHC-6 Twin Otter aircraft. Representative operational flights of the modified DHC-6 will be conducted in 1978 to demonstrate the active control system performance and benefits. The system is expected to significantly improve ride quality for low-wing-loading STOL aircraft, as indicated in the figure. Following completion of these tests, a more extensive short-haul active control design for powered-lift aircraft incorporating envelope limiting, ride quality control, gust load alleviation, maneuver load control, and flight path control will be designed and

evaluated for a Tilt Rotor vehicle. Completion of these evaluations is scheduled for the mid 1979 time frame.

For the long-haul application, represented in figure 12, a series of contracted active control aircraft designs considering reduced static stability, gust and maneuver load alleviation, ride quality and fatigue-life control, envelope limiting, and flutter and structural mode suppression will be conducted for representative subsonic, freighter, transonic, and supersonic missions; and the results will be compared with conventional aircraft designs. The most promising of these designs will then be evaluated in the 1980-1981 time period through design, fabrication and flight tests of a scaled research vehicle which will concentrate on the demonstration of the high-risk technologies essential to validation of the ACA design techniques.

Completion of the ACA program should provide a comprehensive design base for the application of active control.

Active Control Configured Transport

In addition to NASA's work on active control design procedures and systems, a companion program which would carry this technology into practice through actual redesign of a jet transport is under consideration for initiation in mid 1975. This Active Control Configured

Transport (ACCT) program, to be managed by the Flight Research Center, would make direct use of the digital-fly-by wire and active control technology program outputs to redesign a small jet transport, such as a Jetstar or B-737, to evaluate the resultant benefits and penalties in a realistic operational environment. Such a reconfigured aircraft could offer major performance improvements (reference 14) through synergism of active controls and advanced aerodynamic technologies. Figure 13 illustrates some of these potential benefits in terms of relative fuel consumption. While individual contributions of either control or aerodynamic technologies are relatively small, the combination of a fly-by-wire active control system with a high-aspect-ratio supercritical wing design made possible through maneuver-load and gust alleviation can yield appreciable fuel savings. Noise footprints for such an ACCT design could also be reduced by as much as 90%, based on early engineering estimates.

The ACCT program, represented in figure 14, could include an actively-controlled supercritical wing located for optimum static margin and a corresponding new horizontal and vertical tail. To minimize demonstration costs, the associated active control system could be mechanized using the all DFBW system proven during the F-8 program. Extensive ACCT flight

tests would verify the fuel savings and performance and ride quality improvements obtainable with an integrated active control transport design, and would provide invaluable experience on the active control system and aircraft operations in a representative flight environment.

If warranted by the initial conceptual designs and cost/benefit studies, an ACCT test aircraft would be selected in 1976. Design of an active control configuration for this transport could be completed in 1977, and the test aircraft could be modified by 1979 for operational flights in the 1980-1981 time span. By involving potential users throughout the design, implementation, and flight test phases of such a demonstrator, airline, industry, and FAA acceptance of active controls could be significantly accelerated and the associated technology could be made widely available for future transport applications.

CONCLUDING REMARKS

The successful completion of the NASA programs touched on in this brief overview should permit a major step forward in the application of advanced control concepts by providing a better understanding of the associated system and aircraft design problems and benefits. Maximum participation by industry in the

definition and implementation of these programs, and wide dissemination of the resultant design, development, and flight test data will - we hope - be instrumental in bringing about the early realization of the potential of active controls.

We stand on the threshold of a revolution in aircraft design, if we can learn to practically harness the capability of digital avionics and advanced controls. With the increased emphasis on cost-effectiveness and fuel-economy, we must take full advantage of this capability for the development of more efficient and competitive future transports to maintain our leadership role in the marketplace - and in the air.

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NASA ADVANCED CONTROL OVERVIEW

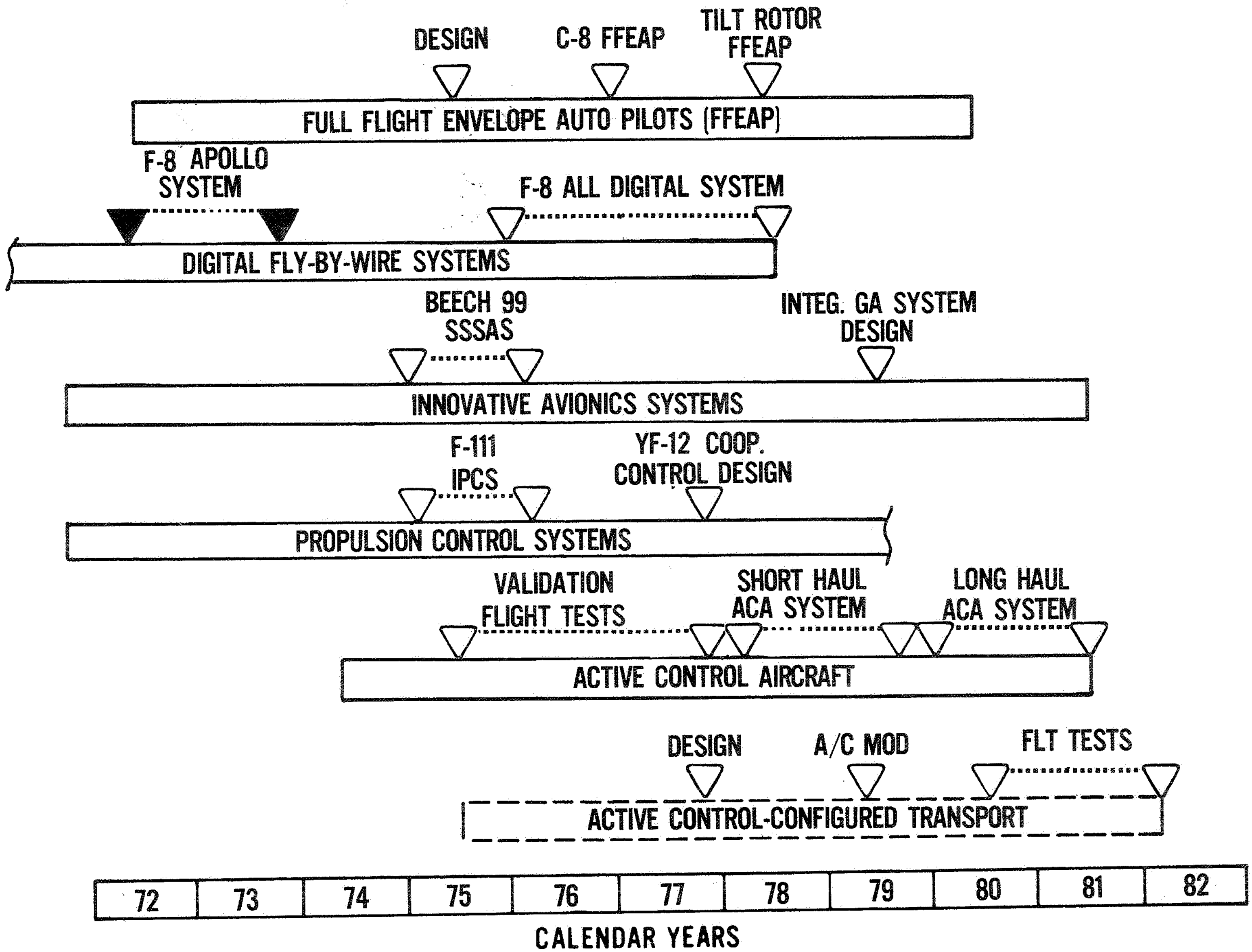


FIGURE 1

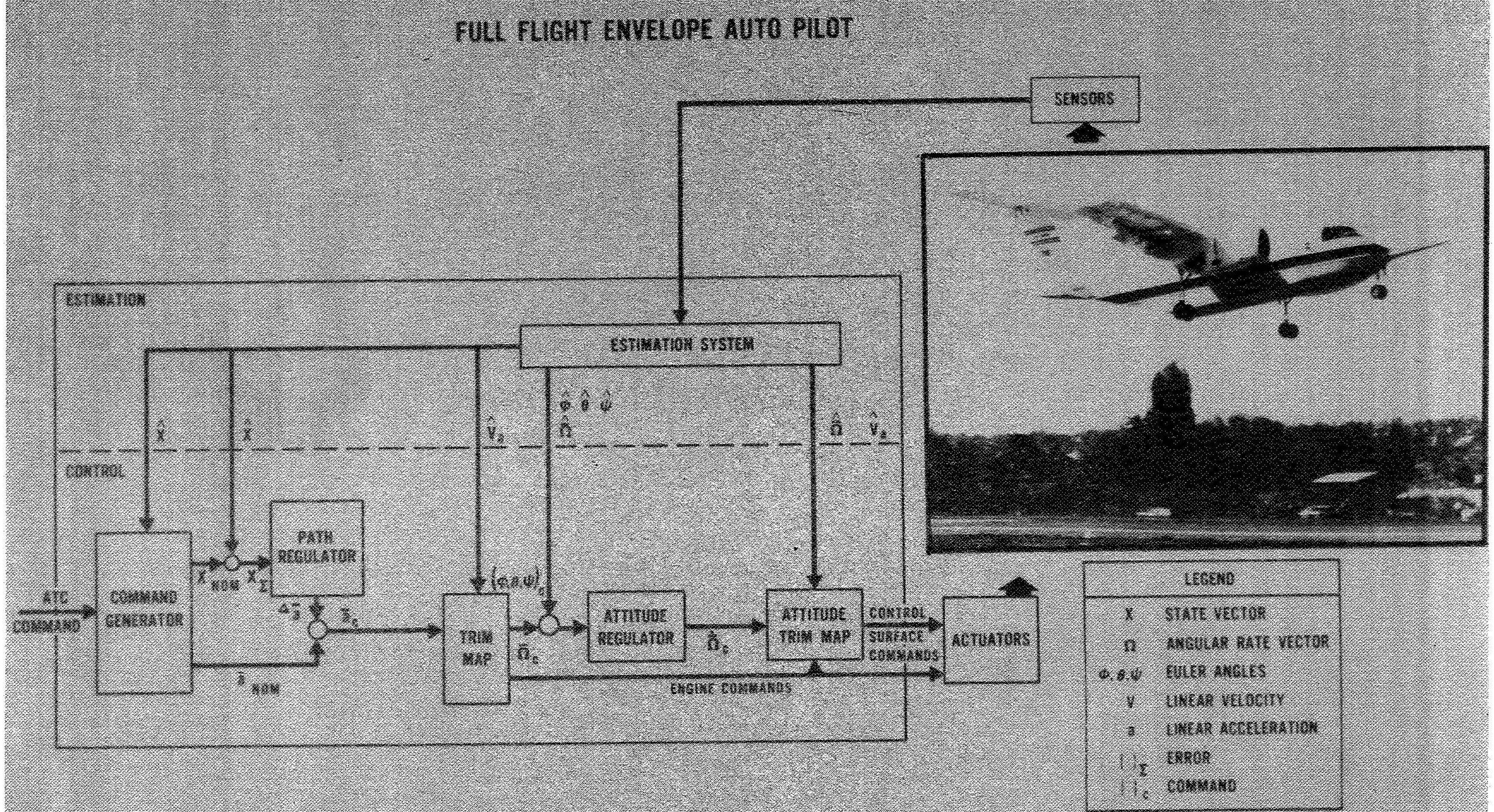

FULL FLIGHT ENVELOPE AUTO PILOT
SENSORS
ESTIMATION
ESTIMATION SYSTEM
CONTROL
ATC COMMAND
COMMAND GENERATOR
PATH REGULATOR
TRIM MAP
ATTITUDE REGULATOR
ATTITUDE TRIM MAP
CONTROL SURFACE COMMANDS
ENGINE COMMANDS
ACTUATORS
LEGEND
X STATE VECTOR
Ω ANGULAR RATE VECTOR
φ, θ, ψ EULER ANGLES
V LINEAR VELOCITY
a LINEAR ACCELERATION
( )Σ ERROR
( )c COMMAND

FIGURE 2

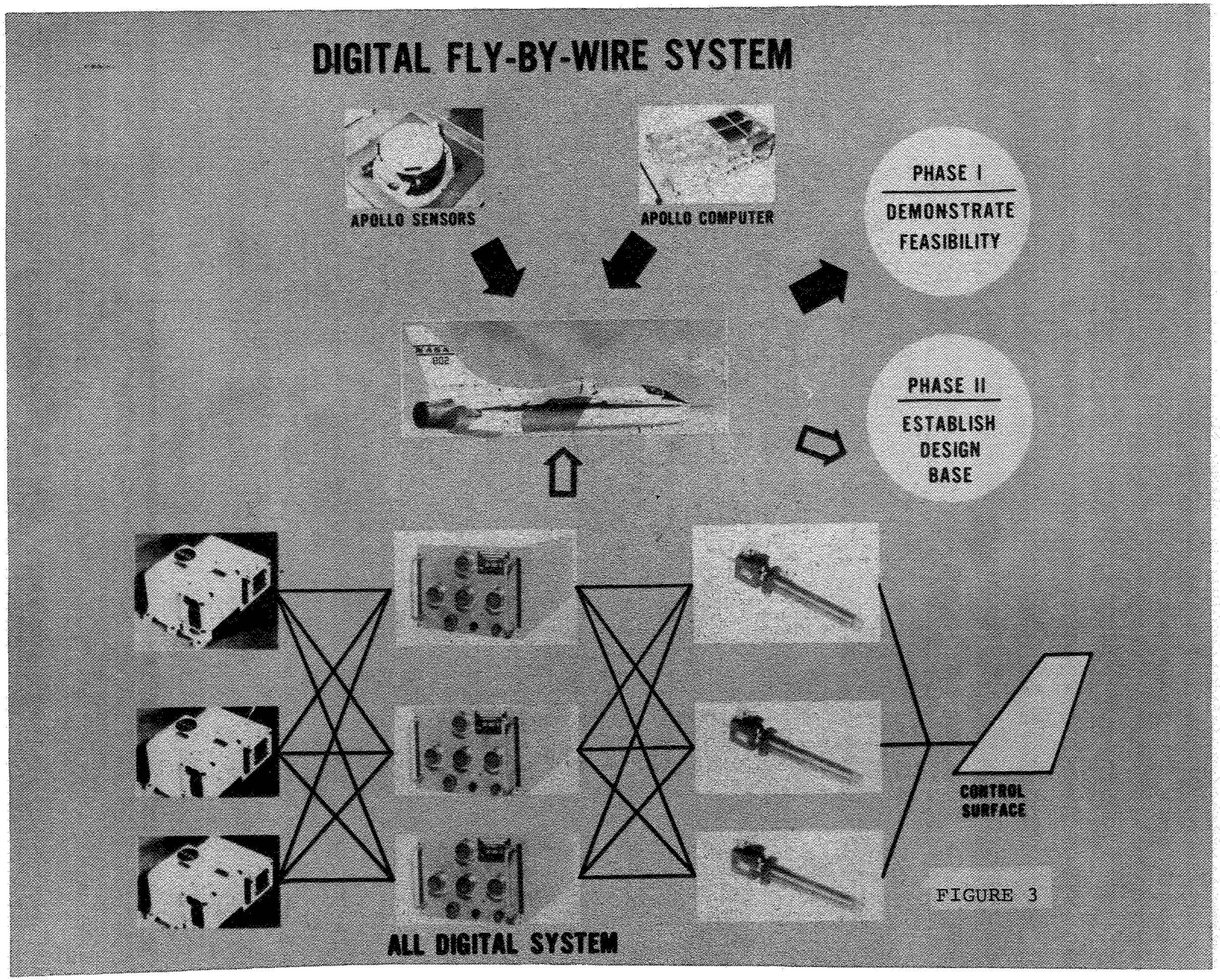

DIGITAL FLY-BY-WIRE SYSTEM
APOLLO SENSORS
APOLLO COMPUTER
PHASE I
DEMONSTRATE FEASIBILITY
PHASE II
ESTABLISH DESIGN BASE
CONTROL SURFACE
ALL DIGITAL SYSTEM

FIGURE 3

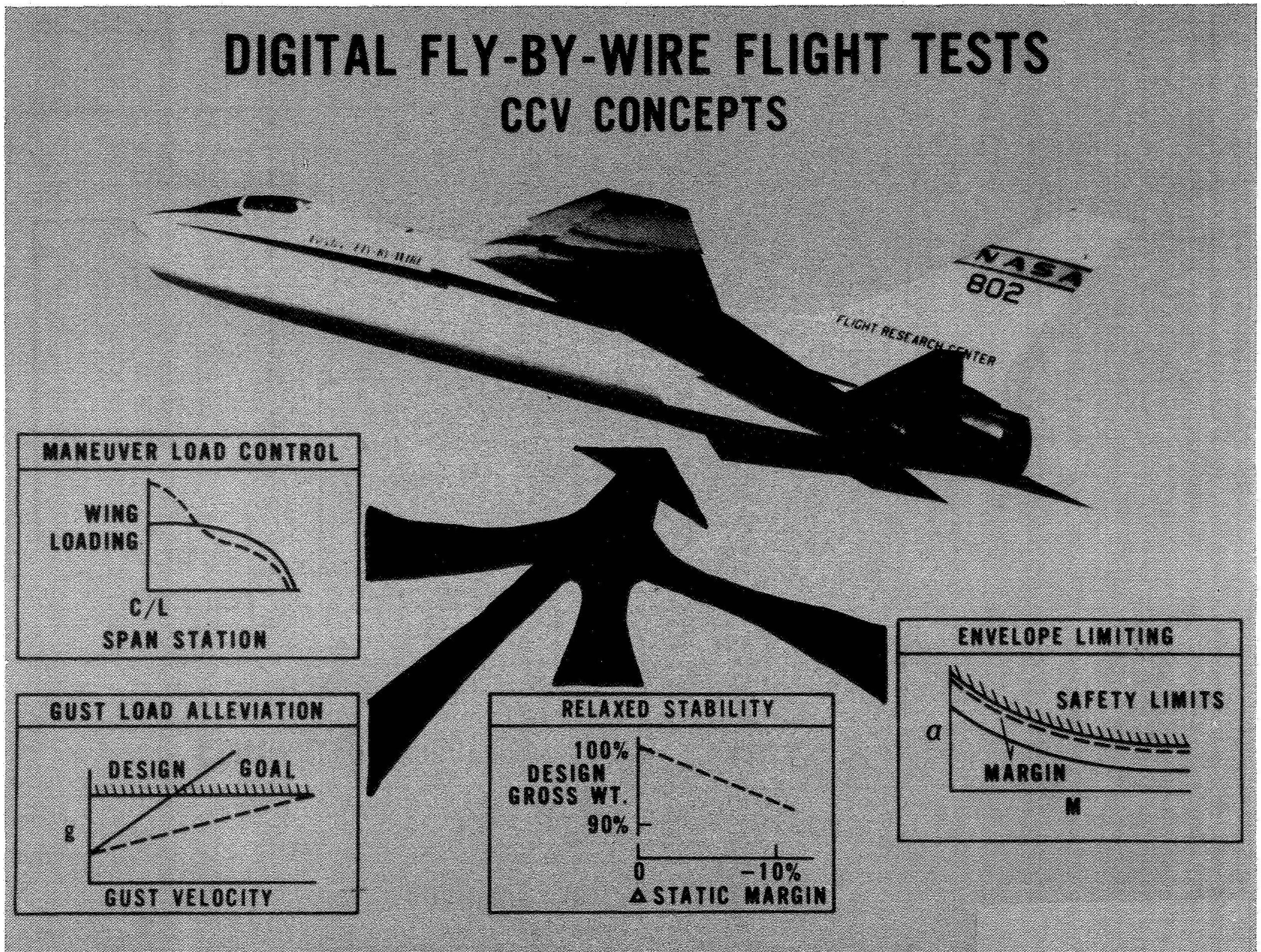

DIGITAL FLY-BY-WIRE FLIGHT TESTS
CCV CONCEPTS
NASA
802
FLIGHT RESEARCH CENTER
MANEUVER LOAD CONTROL
WING LOADING
C/L
SPAN STATION
GUST LOAD ALLEVIATION
DESIGN
GOAL
g
GUST VELOCITY
RELAXED STABILITY
100%
DESIGN GROSS WT.
90%
0
-10%
Δ STATIC MARGIN
ENVELOPE LIMITING
SAFETY LIMITS
α
MARGIN
M

FIGURE 4

DIGITAL FLY-BY-WIRE FLIGHT TESTS

ADAPTIVE CONTROL CONCEPTS

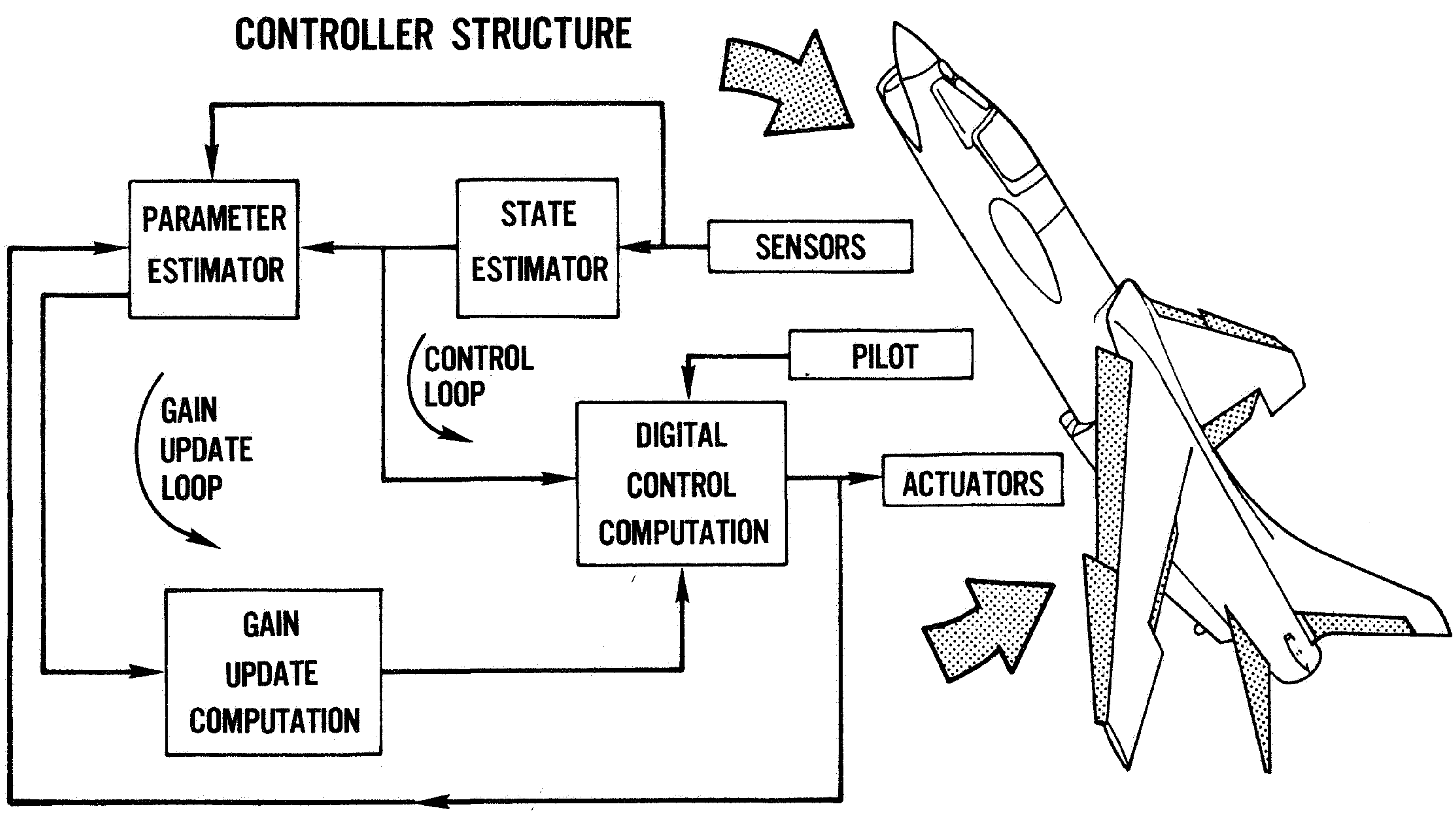
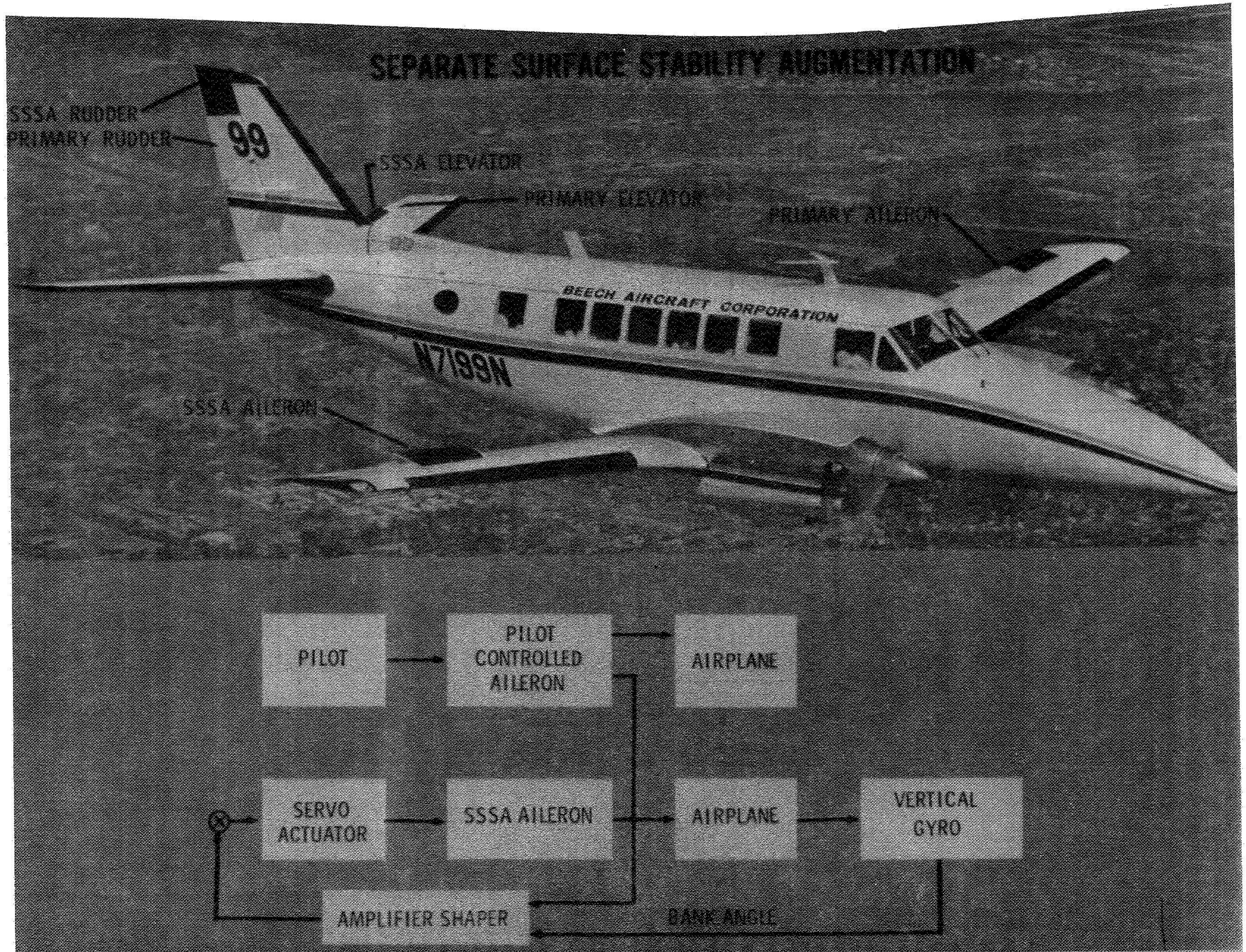


FIGURE 5


SEPARATE SURFACE STABILITY AUGMENTATION
SSSA RUDDER
PRIMARY RUDDER
SSSA ELEVATOR
PRIMARY ELEVATOR
PRIMARY AILERON
SSSA AILERON
BEECH AIRCRAFT CORPORATION
N7199N
99
PILOT
PILOT CONTROLLED AILERON
AIRPLANE
SERVO ACTUATOR
SSSA AILERON
AIRPLANE
VERTICAL GYRO
AMPLIFIER SHAPER
BANK ANGLE
FIGURE 6

INTEGRATED AVIONICS SYSTEM

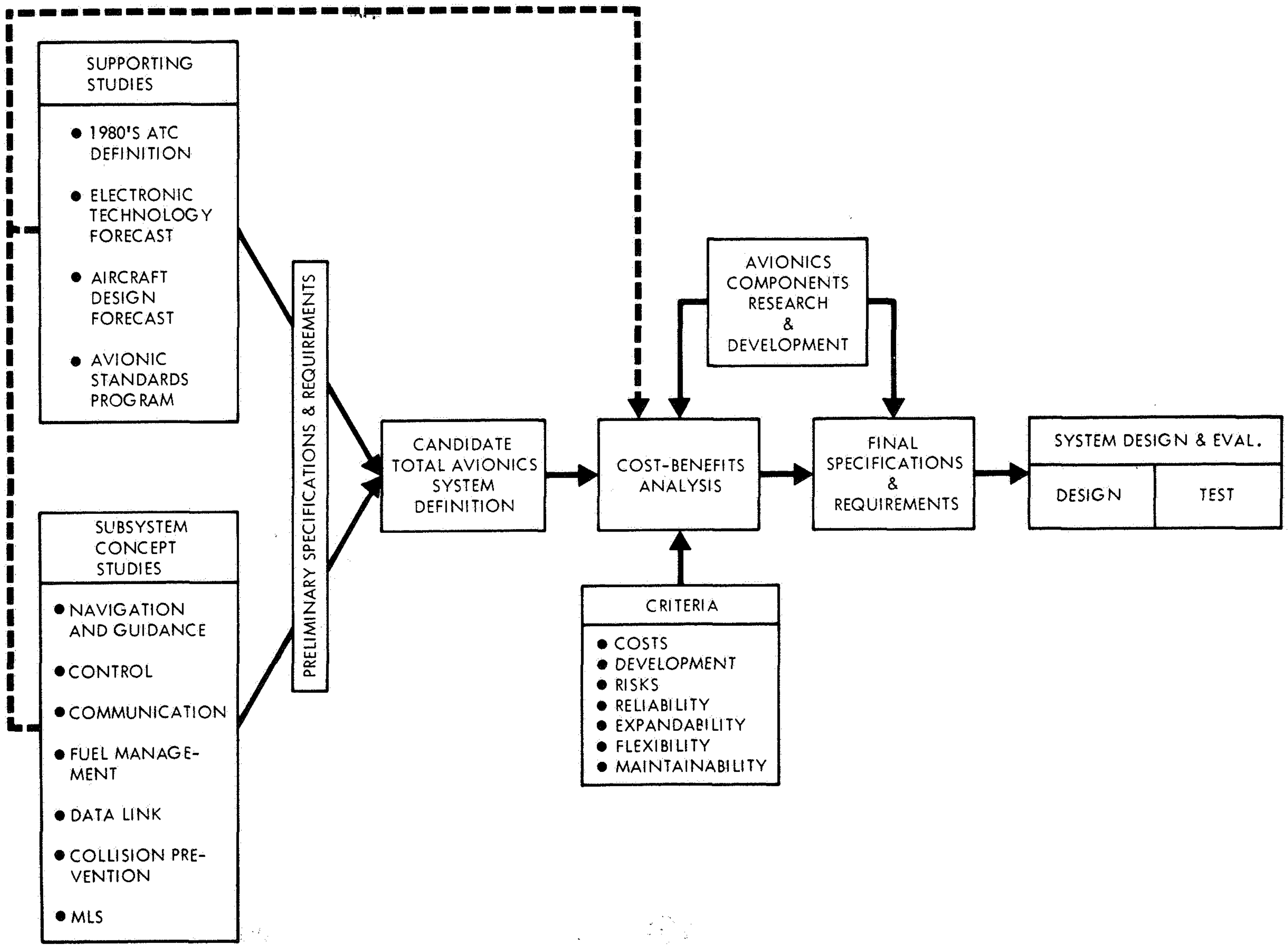


FIGURE 7

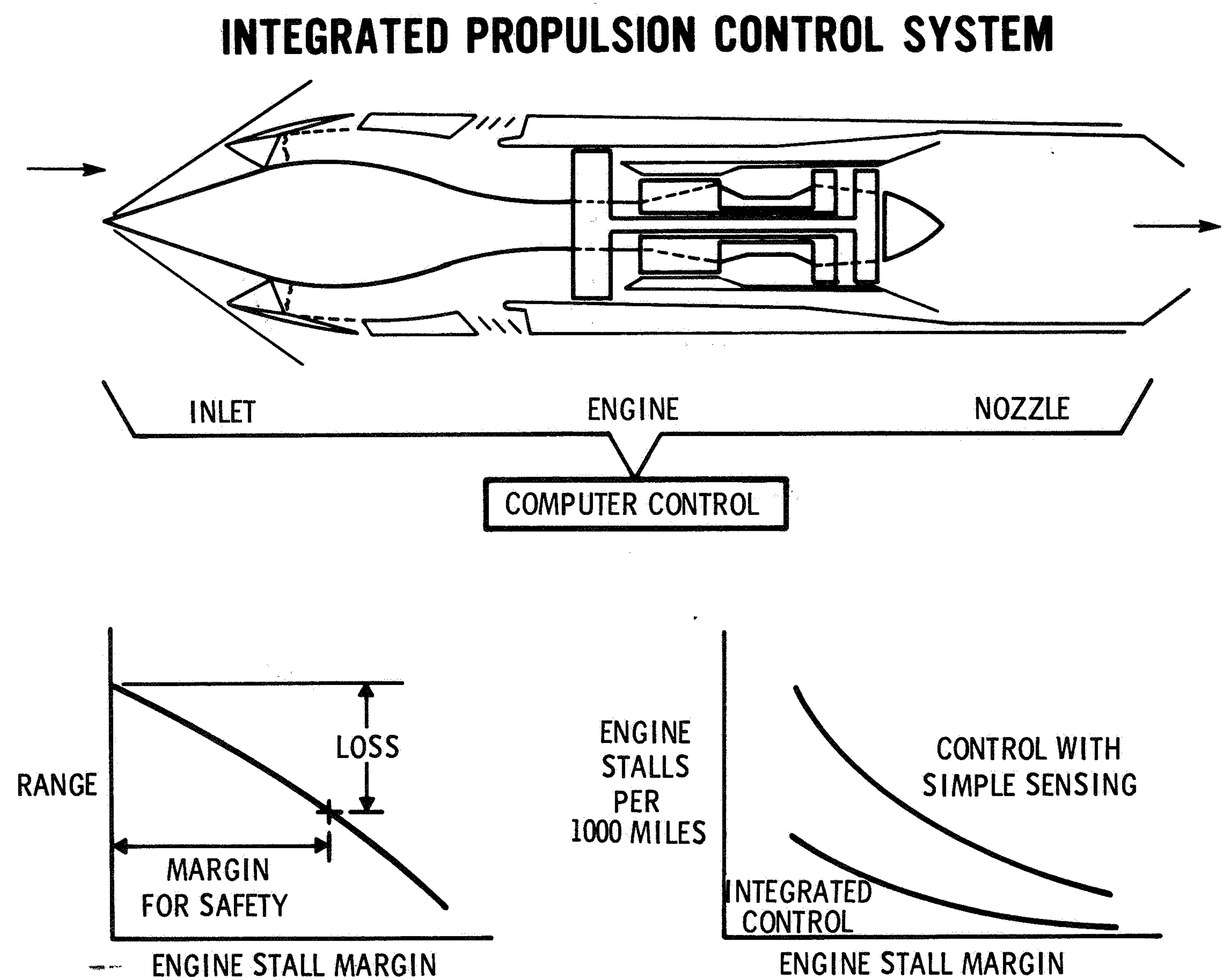

INTEGRATED PROPULSION CONTROL SYSTEM
INLET
ENGINE
NOZZLE
COMPUTER CONTROL
RANGE
LOSS
MARGIN FOR SAFETY
ENGINE STALL MARGIN
ENGINE STALLS PER 1000 MILES
CONTROL WITH SIMPLE SENSING
INTEGRATED CONTROL
ENGINE STALL MARGIN

FIGURE 8

COOP AUTOPILOT/SAS/PROPULSION CONTROL SYSTEM

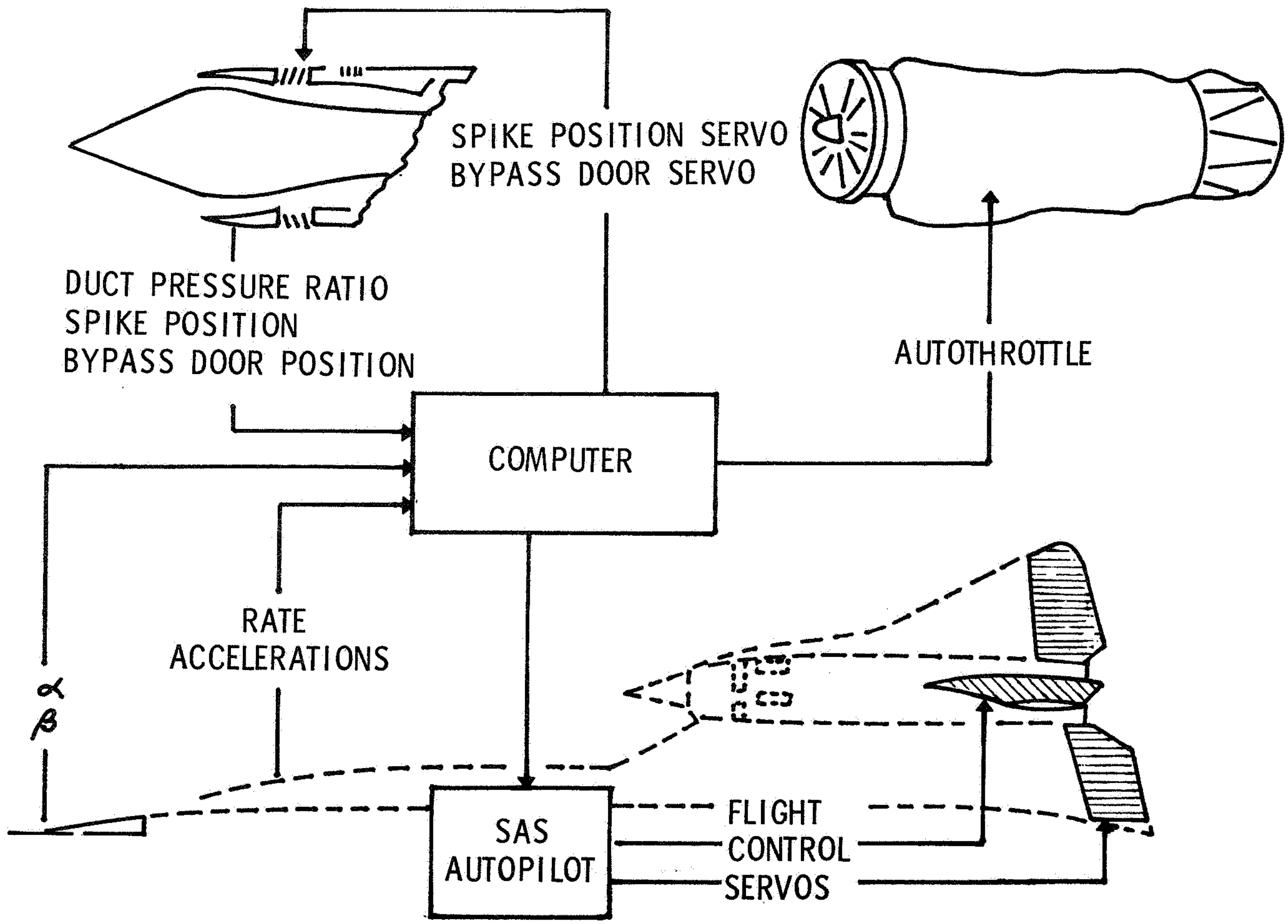


FIGURE 9

COMPUTER-AIDED DESIGN APPROACH

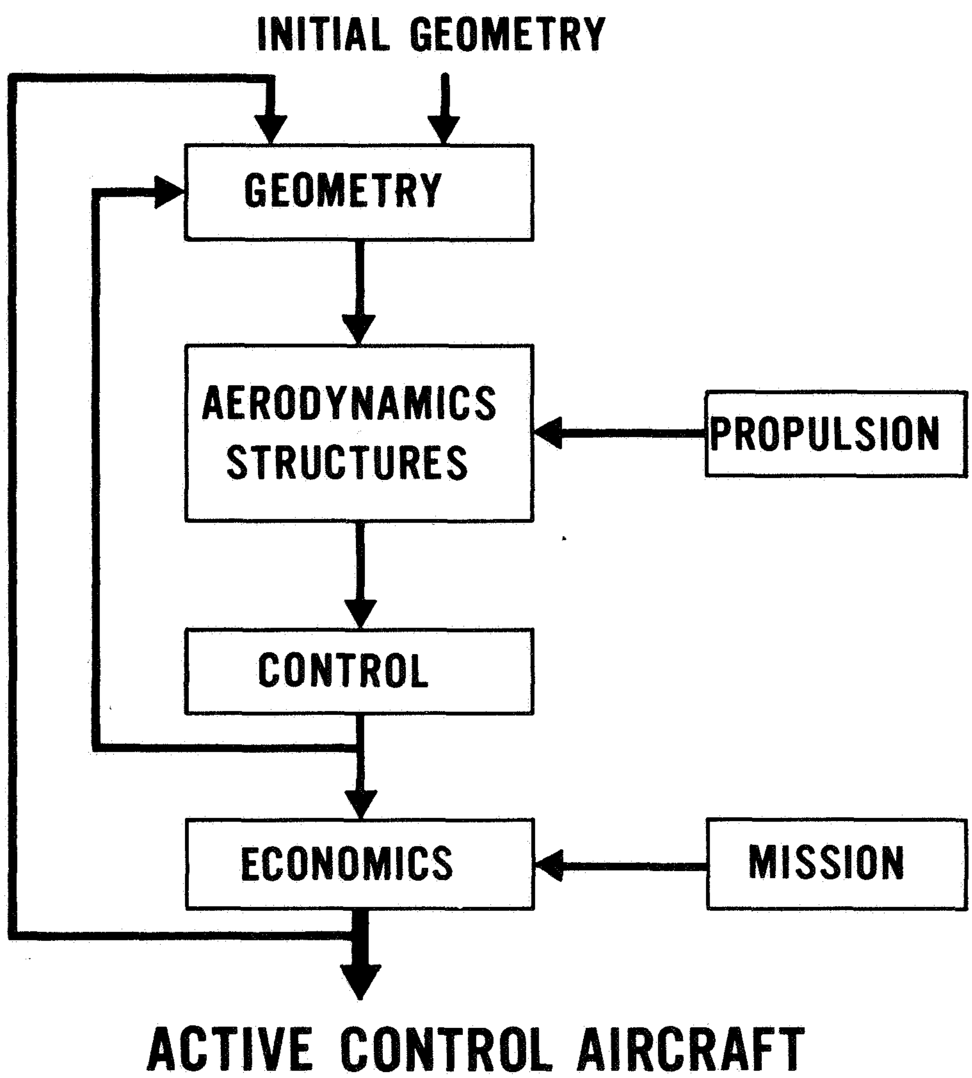
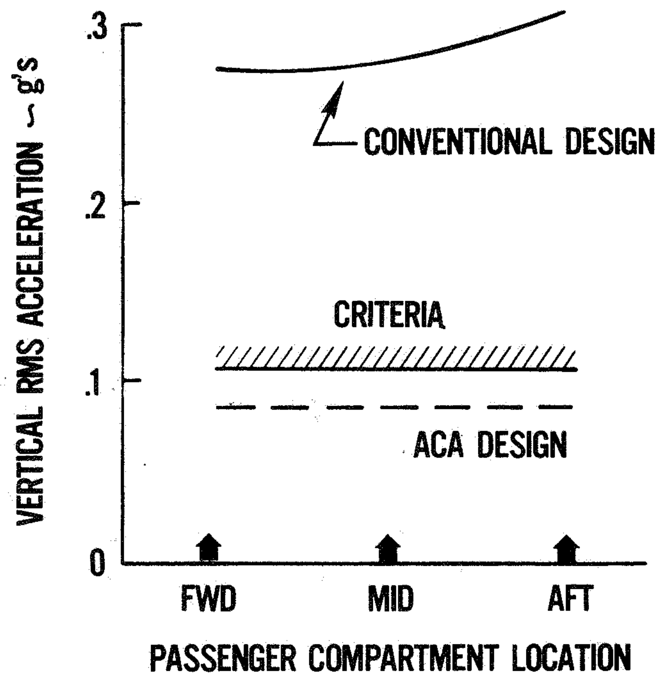


FIGURE 10

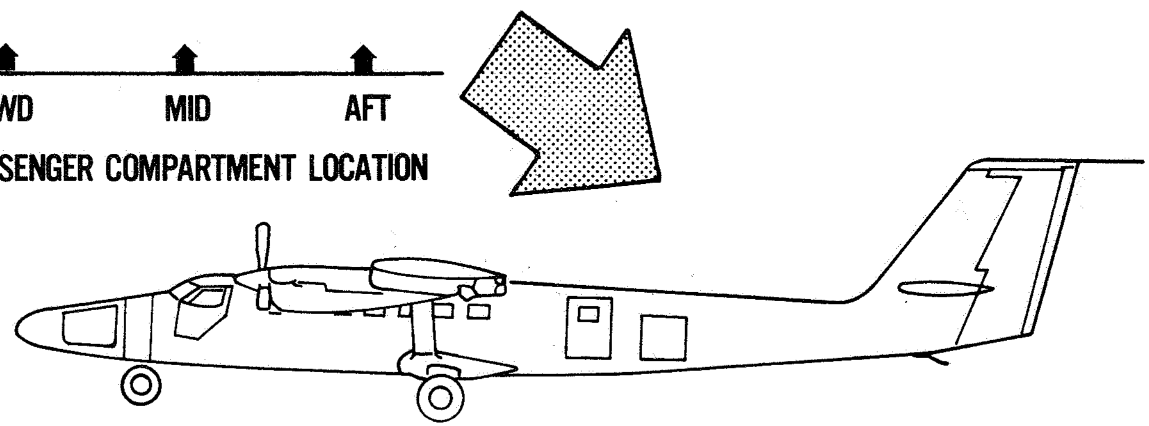
ACTIVE CONTROL AIRCRAFT

SYSTEM DESIGN & VALIDATION



OBJECTIVES

- ACTIVE CONTROL SYSTEM SYNTHESIS
- IMPROVED RIDE QUALITY & TRAJECTORY CONTROL
- OPERATIONAL FLIGHT EXPERIENCE



DHC-6 TWIN OTTER AIRCRAFT

FIGURE 11

ACTIVE CONTROL AIRCRAFT
HIGH-RISK CONCEPT VERIFICATION

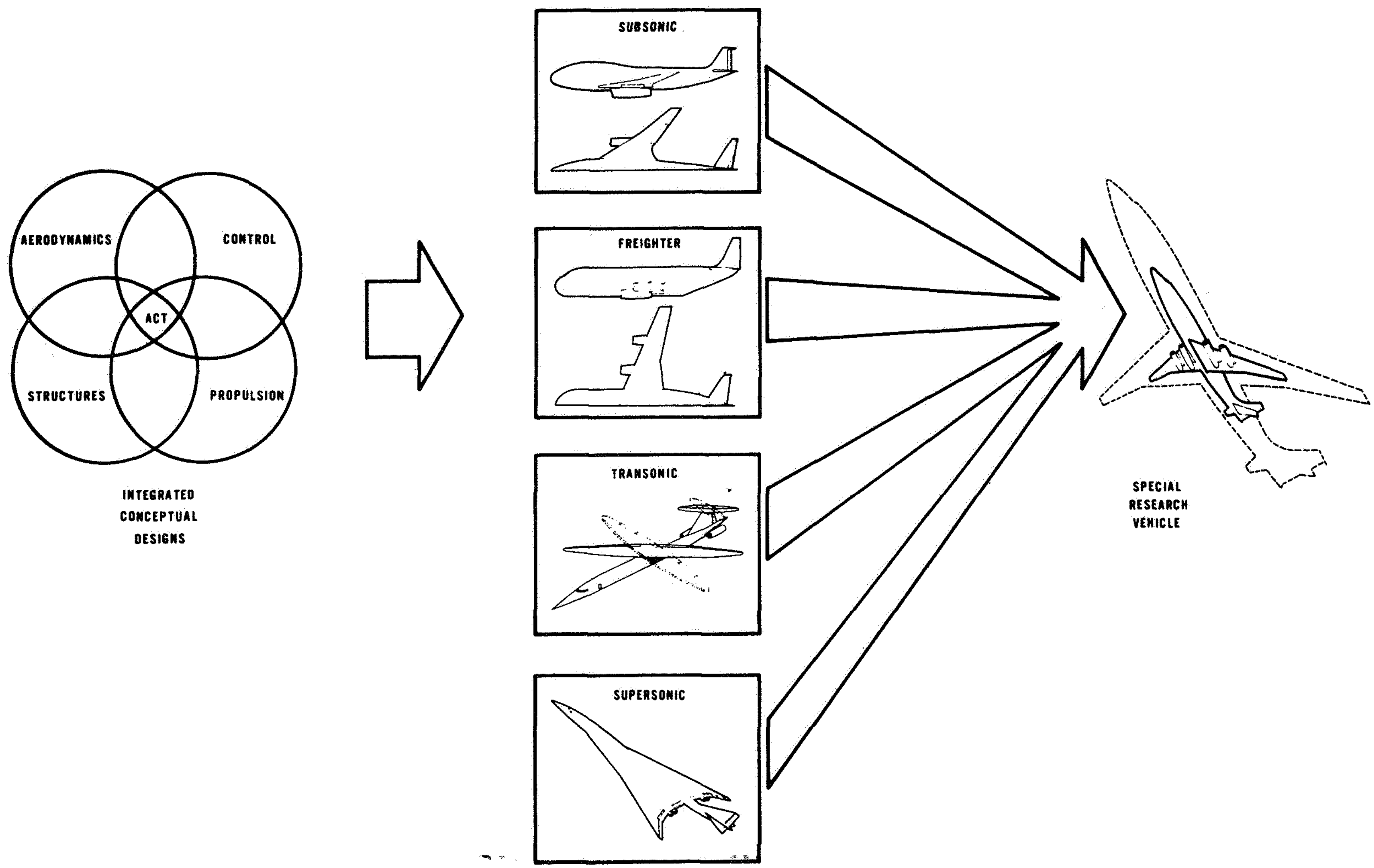


FIGURE 12

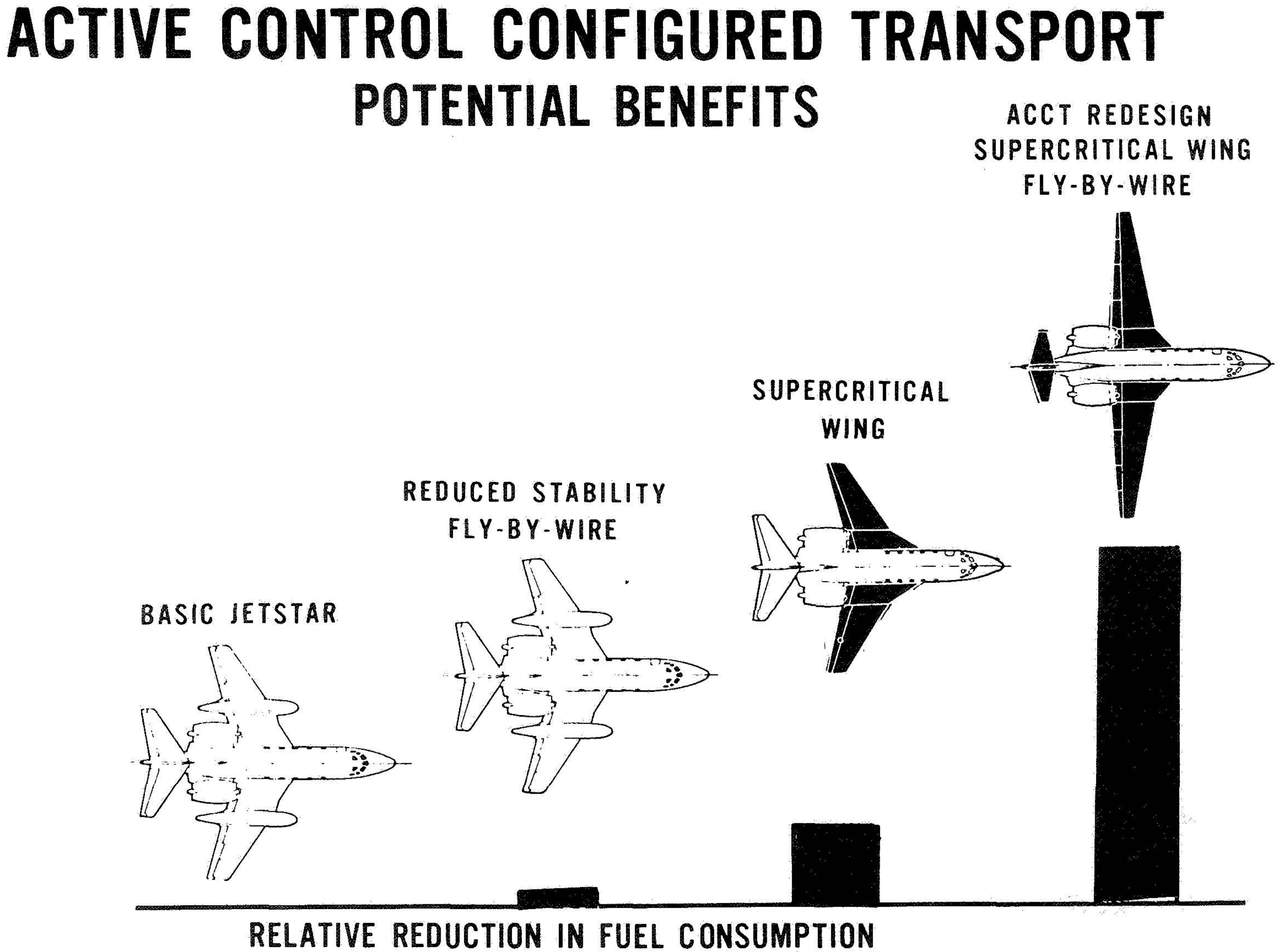

ACTIVE CONTROL CONFIGURED TRANSPORT
POTENTIAL BENEFITS
ACCT REDESIGN
SUPERCRITICAL WING
FLY-BY-WIRE
SUPERCRITICAL
WING
REDUCED STABILITY
FLY-BY-WIRE
BASIC JETSTAR
RELATIVE REDUCTION IN FUEL CONSUMPTION

FIGURE 13

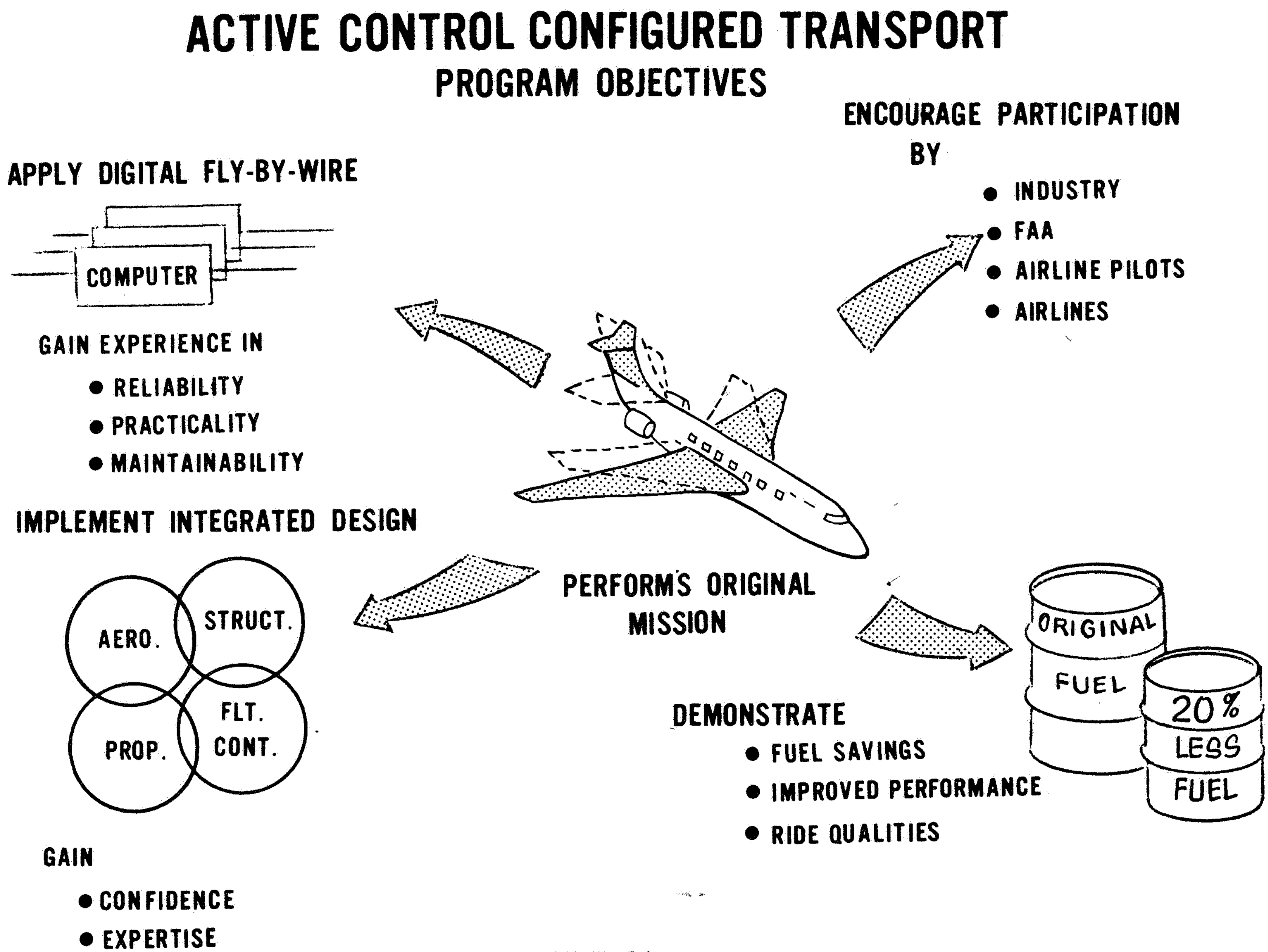

ACTIVE CONTROL CONFIGURED TRANSPORT
PROGRAM OBJECTIVES
APPLY DIGITAL FLY-BY-WIRE
COMPUTER
GAIN EXPERIENCE IN
● RELIABILITY
● PRACTICALITY
● MAINTAINABILITY
IMPLEMENT INTEGRATED DESIGN
AERO.
STRUCT.
PROP.
FLT. CONT.
GAIN
● CONFIDENCE
● EXPERTISE
ENCOURAGE PARTICIPATION BY
● INDUSTRY
● FAA
● AIRLINE PILOTS
● AIRLINES
PERFORMS ORIGINAL MISSION
DEMONSTRATE
● FUEL SAVINGS
● IMPROVED PERFORMANCE
● RIDE QUALITIES
ORIGINAL FUEL
20% LESS FUEL

FIGURE 14